Muon excess following a gamma-ray burst event detected at the International Space Station

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Abstract: At UT 2012-04-24 16:47:14, the Gas Slit Camera (GSC) of the Japanese Monitor of All-sky X-ray Image (MAXI) instrument on the International Space Station (ISS) detected a short x-ray transient lasting about 34 seconds. The MAXI/GSC transient was most likely a gamma-ray burst (GRB), because of the high galactic latitude, spectral hardness ratio and the absence of known bright x-ray source at the detected position. In addition, the MAXI/GSC transient coordinates were in the field of view of the inclined Tupi muon telescope located at ground (3 m above sea level) at in the South Atlantic Anomaly (SAA) region. We report here that the Tupi telescope registered a muon excess with a signal significance 6.2 $\sigma$ within the MAXI/GMC transient time period. Assuming a power law function with a spectral index of -1.54 in the tail of the primary gamma ray energy spectrum, we can conclude that the fluence obtained from the muon excess detected by the Tupi telescope is consistent with the preliminarily value obtained by the MAXI team.

Keywords: gamma ray astronomy, gamma ray burst, atmospheric effect.

1 Introduction

At random times and from random directions, lasting from milliseconds to many minutes, there are flashes of gamma rays associated with extremely energetic explosions in the Universe. They are known as gamma-ray bursts (GRBs). These bursts are often followed by an afterglow at longer wavelengths (X-ray, ultraviolet, optical, infrared, microwave and radio) that allows to pinpoint the origin of the GRB. According to the current understanding, the energy at the source of a GRB does not escape from the explosion uniformly, but is focused into two oppositely-directed jets. Previously it was shown that a substantial fraction of GRBs have photon spectra which extend at least to tens of GeV, at a rate of $\sim 3 - 5yr^{-1}$ [1] In some GRBs the high energy (GeV) component arrives with a considerable delay with respect to the lower energy (keV) component [2, 3], while in others, for instance in GRB090926 and GRB090217, the delay was small or negligible [4]. It is generally believed that high energy emission holds clues to the exact mechanisms of GRBs and their afterglow. Numerous emission scenarios can be considered, ranging from synchrotron and inverse-Compton emissions to photoproduction [5, 6, 7, 8].

So far, the ground based Tupi experiment with the muon telescopes has reported extensive observations of small transient events such as energetic solar flares of small scale cataloged as C-class, detected in association with the GOES and Fermi spacecrafts [9, 10], interplanetary shocks of diverse origins (coronal mass ejection and corotating interaction regions) in association with the ACE and SOHO spacecrafts [11, 12], as well as some possible GeV counterpart of GRBs, such as a delayed connection [13], a prompt connection [14] and an early connection [15]. In the case of GRBs the sea-level muons in gamma showers are mainly produced in a photoproduction process of the primary photon.

The locations of GRBs are mainly detected in real-time by spacecrafts (Fermi, Swift, Integral, Wind-Konus). On the ground, various optical telescopes can respond within seconds to signals sent through the Gamma-ray burst Coordinates Network (GCN). Nowadays, among many remarkable detectors in operation there is theMonitor of All-sky X-ray Image (MAXI), the first astronomical payload installed on the Japanese Experiment Module - Exposed Facility (JEM-EF or Kibo-EF) on the International Space Station (ISS) [16]. It can cover about 85% of the whole sky every orbit ($\sim$ 90 minutes). MAXI has detected short transient events such as gamma-ray bursts and stellar flares, many in association with other GRB satellite experiments. Here we report new results from the Tupi experiment in association with the MAXI/GSC instrument. On April 24, 2012 MAXI/GSC detected a short X-ray transient lasting about 34 seconds, with the preliminary flux ($4 - 10$ keV) of the source $170 \pm 30$ mCrab [17]. Because of its high galactic latitude, spectral hardness ratio and the absence of known bright x-ray source at the detected position ($R.A., Dec.) = (+23.985^0, -29.879^0$), this MAXI/GSC transient was probably a gamma-ray burst (GRB 120424A). The Tupi telescope registered a muon excess with a signal significance of 6.2 $\sigma$ within the MAXI/GMC transient time period. We show that from the characteristics of the muon excess detected in the Tupi telescope, this signal can possibly suggest that the muon excess is due to photonuclear reactions in the Earths atmosphere induced by gamma rays with energies up to above 10 GeV. Thus, the muon excess observed at the ground could be an indication of the high energy tail of a GRB.
The Tupi scaler mode consists in recording coincidences rates (scalers) between the two detectors of each telescope. Each counter detector register signals above the threshold value, corresponding to an energy of $\sim 100\text{MeV}$ deposited by particles (muons) that reach the detector.

Each telescope was constructed on the basis of two detectors (plastic scintillators 50 cm x 50 cm x 3 cm) separated by a distance of 3 m. Of the six telescopes in operation, we would like to point out two of them that work with a counting rate of up to 30 MHz. One telescope has a vertical orientation, and the other one is oriented at 45 degrees to the vertical (zenith), pointing to the west. Each telescope counts the number of coincident signals in the upper and lower detector. In addition, each telescope uses a veto or anti-coincidence guard system of a third detector close to the two telescopes. For instance, this system allows only the detection of muons traveling close to the axis of the telescope. The telescopes are situated inside a building under two flagstones of concrete, allowing to the axis of the telescope. The telescopes are situated inside a building under two flagstones of concrete, allowing registration of muons with energy threshold around $E_{th} > 100\text{MeV}$, required to penetrate the two flagstones. Time synchronization is essential for correlating event data in the Tupi experiment. The GPS receiver (Tupi) outputs Universal Time (UT).

The data acquisition system is mounted on the basis of virtual instrument technique, that is, the analogical signal of each detector is read for a PCI card and all the steps, such as the signal discrimination, coincidences and counting are implemented via software Fig. 1 summarize the situation. The data acquisition diagram is shown in the left figure, and a photograph of the inclined telescope (where the muon excess in association with the MAXI/GSC transient has been found) is presented in the right figure.

The effective field of view of each Tupi telescope is estimated as $\Omega_{eff} \sim 0.37\pi r = 0.118\pi r$, around 8 times smaller than the water Cherenkov tank detector and a typical neutron monitor detector whose effective field of view is near $\pi$. Thus, the narrow solid angle of the Tupi telescopes is another difference in comparison with the Cherenkov tank detector and neutron monitor detector solid angle.

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3 Observations

On April 24, 2012 at 16:47:14 UT the MAXI/GSC instrument on the ISS detected a short Xray transient lasting about 34 seconds within the 40 seconds triangular transit response of MAXI/GSC. Assuming that the source flux was constant over the transit, the transient triggered by MAXI/GSC showed the source position at (R.A.,Dec) = (+23.985, −29.897)/(01:35:56.4,−29:52:44.0)(J2000), which has a statistical uncertainty of 16 arc min at the 90% confidence limit and an additional systematic uncertainty of 6 arcmin (90% containment radius) [17] There was no known bright X-ray source at the detected position. The event was at high galactic latitudes. Based on these observations, and also due to the spectral hardness ratio, this MAXI/GSC transient indicated that the transient was probably a gamma-ray burst (GRB 120424A). On 24 April 2012 a sharp peak with a significance of 6.26 at 68% confidence level was found in the 24 hours raw data (counting rate at 1 Hz) of the inclined Tupi telescope (see Fig. 2). The Tupi peak with duration 1 sec was within the MAXI/GSC time interval. It was possible to recognize this peak in the time profile of the muon counting rate just by naked eye (see Fig. 2). The Tupi signal significance was calculated according to the bin selection criteria (BSC) algorithm. According to this algorithm, the signal statistical significance $S$ in the i-th bin is defined as $s_i = (C_i - B)/\sqrt{B}$ where $C_i$ is the measured number of counts in the i-th bin and $B$ is the average background count.

From a cross check with the GCN circular, it was found that the muon excess (peak) occurred 10 seconds after the

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**Fig. 1**: Left: General layout of the Tupi telescope including the logic in the data acquisition system using the virtual instrument technique. Right: Photograph of the Tupi inclined telescope (45 degree relative to the vertical) and pointing to the West.

**Fig. 2**: Top panel: The raw data observed in the inclined Tupi telescope on April 24, 2012. Bottom panel: Statistical significance (number of standard deviations) of the 1-sec binnning counting rate observed by the inclined W45 Tupi telescope, both as a function of the time elapsed since the MAXI/GSC transient 120424A trigger time. The red bold lines represent the MAXI event duration.
All the time bins (each of 1 sec duration) of the inclined Tupi telescope have been tested by the BSC algorithm. The BSC function follows a Gaussian distribution if there is no signal. A confidence analysis has been made for a one hour interval around the MAXI/GSC GRB 120424A trigger time. The results are shown in Fig. 4. From this analysis, it is possible to identify three categories of particles in our observation. First, there is the muon background from the galactic cosmic ray component that follows a Gaussian distribution (solid line (A) in Fig. 4). Second, there are muons due to high energy precipitation of trapped and quasitrapped particles in the SAA region (solid line (B) in Fig. 4). The low energy cosmic ray flux in the SAA region is even higher than the world averages at comparable altitudes. In the present case this component does not exceed 10% of the galactic component, and it is consistent with a Gaussian distribution. And third, there is an event with a signal significance of 6.2σ indicated by a vertical arrow. This event corresponds to the muon excess coincident with the MAXI/GSC GRB120424A.

4 Confidence analysis

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5 Spectral analysis

The energy spectra of gamma-ray bursts display a diverse phenomenology. The spacecrafts observed gamma rays up to 33 GeV [3]. While some energy spectra can be fitted by a simple power law form over many decades [20], others require a few separate components to explain the high energy emission [21]. Some GRBs do not indicate any cutoff in the spectrum. In most of the cases there can be seen an exact power law solution, which suggests that even higher energy photon emission could be detected. However, above 33 GeV, there have been only upper limit estimations to the GRB flux[22, 23, 24]. We assume here that the energy spectrum of gamma rays with energies above 10 GeV, that is, in the high energy region (the tail of the spectrum) of a GRB, can be fitted by a single power law function

\[ J(E) = A \gamma \left( \frac{E}{10 \text{ GeV}} \right)^\gamma. \]  

In this equation there are two unknown quantities, the coefficient \( A \) and the spectral index \( \gamma \). The convolution of a yield function \( S(E) \) (number of muons per gamma ray) and the particle spectrum \( J(E) \) gives the response function, that is the number of muons in the excess signal generated by the GRB photons during the time period \( T \). This convolution can be expressed as

\[ N_M = S_{eff} \times T \int_{E_{min}}^{\infty} S(E)J(E,T)dE. \]  

To obtain the yield function, we have used the results of the FLUKA Monte Carlo simulation [24]. In this framework the minimal effective energy of a gamma ray to produce muons in the atmosphere is \( \sim 10 \text{ GeV} \). The muon excess allows us to obtain the coefficient \( A \) of the primary GRB spectrum as follows:

The Tupi fluence (during one second) is estimated as \( (1.78 \pm 0.40) \times 10^{-7} \text{erg/cm}^2 \) in the energy range above 10 GeV. This is close to the preliminarily integrated time fluence reported by the MAXI team 170 ± 30 mCrab during 34 seconds, that is equivalent to \( 1.62 \times 10^{-7} \text{erg/cm}^2 \) in the (4-10 keV) energy range. Fig. 5 summarizes the situation.

6 Conclusions

(1) We have reported the detection of a muon excess flux (above the background) as \( (3.33 \pm 0.74) \times 10^{-3}\text{cm}^{-2}\text{s}^{-1} \) with 68% CL. It can be interpreted as due to photons with energies over 10 GeV from GRB120424A, a transient event with strong features of being the gamma-ray burst observed by the MAXI/GSC instrument on the ISS.
Fig. 5: Gamma ray fluence (time integrated intensity) as a function of the burst T90 duration time. The duration parameter T90 is the time over which a burst emits from 5% of its total measured counts to 95%. Solid circles show Swift BAT gamma ray fluence and the open circles show the Tupi fluence for two different spectral indices.

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